



Shrub encroachment and climate change increase the exposure to drought of Mediterranean wood-pastures

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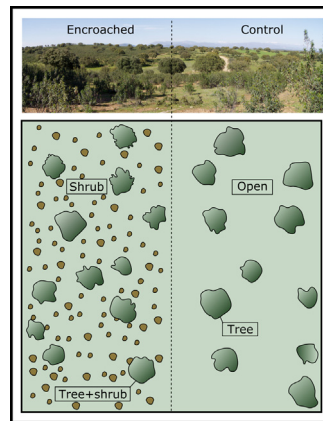
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HIGHLIGHTS

- Mediterranean wood-pastures are threatened by shrub encroachment and climate change.
- We used a water balance model to evaluate drought exposure under current a future climate.
- Encroached plots had more extended droughts and higher usage of deep water than control plots.
- Drought will start earlier in encroached plots under future climate scenarios.
- Higher inter-annual variability was observed when a deep-rooted shrub was present.

GRAPHICAL ABSTRACT



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ABSTRACT

Pastures and wood-pastures, livestock grazing systems where scattered trees and shrubs co-occur, are essential for global food supply. The grazing value of these systems, which is closely related to soil moisture, is increasingly threatened by changes in climate variability and vegetation structure, mainly by shrub encroachment. However, it remains relatively unexplored to what extent the concurrent effect of climate change and shrub encroachment will affect the exposure to drought stress of Mediterranean wood-pastures — defined as a period where soil water availability drops below 40%. Here we combined soil moisture measurements and a process-based water balance model to assess the effect of shrubs, a shallow- and a deep-rooted, on soil moisture under current (2009–2012) and future weather (i.e. RCP4.5 and RCP8.5). Soil moisture was measured and predicted in six sites, three for each type of shrub, where two adjacent plots were selected, a control and an encroached plot. During 2009–2012, encroached plots had more extended droughts (29 and 48 days longer in sites encroached with shallow- and deep-rooted shrubs, respectively) and higher usage of deep water (~30%) than control plots. Under future climatic projections, our results show a consistent increase in the duration, an earlier onset of drought and higher reliance on shallow water with time, particularly under the worst climatic scenario. Encroached plots showed higher inter-annual variability than control plots, particularly in plots encroached with the deep-rooted shrub. Our results indicate that the presence of shrubs magnify the effect of climate. This suggests a likely increase in the exposure of Mediterranean wood-pastures to drought if processes of shrub encroachment persist in a context of climatic changes where earlier and more prolonged droughts will become more frequent.

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1. Introduction

Future climate is expected to be drier by the end of the century in many regions of the world. This is particularly true in the Mediterranean region, where the certainty of model predictions towards increased aridity is high (IPCC, 2014). In Mediterranean wood-pastures, the lack of precipitation during summer shapes the duration and timing of the water stress period (Joffre and Rambal, 1993) and compromises their productivity (Moreno and Cubera, 2008). Thus, an increase in water scarcity, in this already water-limited system, can have profound consequences on its sustainability due to the reduction of its grazing capacity (Daliakopoulos et al., 2017). Concurrently, the abandonment of less favoured lands and traditional practices due to socioeconomic changes in the last decades has led to a marked increase in the density and cover of shrubs (Fernández-Ales et al., 1992; Listopad et al., 2018; Rolo et al., 2016). Shrubs have the capacity of modifying ecosystem functions and ecohydrological processes (e.g. carbon cycling and water yield; Huxman et al., 2005). However, little is known about how the concurrent effects of climate change and shrub encroachment will affect ecohydrological processes and, therefore, soil moisture dynamics of Mediterranean wood-pastures.

The scattered-tree structure of Mediterranean wood-pastures has resulted from long-term management actions that aimed at equilibrating canopy density with climate and soil resources and, therefore, limiting the effect of seasonal drought (Joffre and Rambal, 1993). In this context, the expected impact of the proliferation of shrubs in Mediterranean wood-pastures is the increased usage of soil nutrients (Rivest et al., 2011b) and soil moisture (Cubera and Moreno, 2007). Moreover, soil moisture may be further reduced due to increased interception losses by shrubs canopies (Huxman et al., 2005). As a result, shrubs have been shown to affect the functioning of formerly isolated trees (Rolo and Moreno, 2011) and reduce herbage yields (Rivest et al., 2011a). During periods of reduced precipitation, shrub species with an exploitative use of shallow soil water can impair the persistence of scattered-tree systems (Caldeira et al., 2015). Eventually leading to a degradation trend if the production of pasture cannot sustain profitable livestock densities or if the tree cover goes locally extinct (Moreno and Pulido, 2009).

This conspicuous negative perception of shrubs has been challenged by increasing evidence highlighting the importance of species-specific effects (Eldridge et al., 2011). Shrub presence can also have neutral to positive impacts on soil water content (Moro et al., 1997; Prieto et al., 2010), indicating that the net outcome of shrub encroachment could be dependent on the morphological and functional traits of the encroaching species (Eldridge et al., 2011). For instance, variation in shape and height among shrub species can affect soil surface shading and influence water losses by evaporation to the atmosphere (Villegas et al., 2010). Similarly, differences in rooting systems can shape water usage at different soil depths or patterns of water redistribution within the soil profile (Collins and Bras, 2007). However, much less is known about the effect of different functional types of shrubs on soil water availability under projected climatic scenarios.

Shrub encroachment by deep-rooted shrub species may magnify the consequences of climate change as future climate projection predicts a declining availability of deep water (Schlaepfer et al., 2017). The increased usage of deep soil water may threaten the provisioning of ecosystem functions in a dryer climate because deep water is essential to maintain the functionality of trees embedded within the pasture matrix, particularly at the end of the dry season. Nevertheless, assessing the response of soil water availability to the concurrent effect of shrub encroachment and future climatic projections is complex. For instance, in some drylands where climatic trends predict an increase in precipitation, changes in vegetation structure can lead to a net reduction of soil water availability due to increases in interception losses (Tietjen et al., 2017). Additionally, it is uncertain how the effect of different functional groups of shrubs will affect soil water availability if mean annual

precipitation patterns remain unchanged, but not the temporal availability of water. Precipitation variability is expected to increase, both spatially and temporally, in future climatic scenarios, and a higher variability is likely to lead to extreme weather events, such as droughts (Anderegg et al., 2013). Vegetation production is strongly affected in a highly variable climate because of the recurring cycles of droughts and floods. Indeed, a significant reduction in livestock grazing capacity has been linked to increased inter-annual precipitation variability (Sloat et al., 2018). If the effect of shrubs amplifies inter-annual variability, then the presence of droughts may be more frequent and even decoupled from the occurrence of weather extremes (D'Odorico et al., 2000).

The present study aimed at assessing soil water dynamics under current and future climate in wood-pastures of SW Spain that have undergone a process of shrub encroachment in the last decades because of the abandonment of traditional practices. In particular, we assessed the effect of two contrasting shrub species, a shallow-rooted (*Cistus ladanifer* L.) and a deep-rooted shrub (*Retama sphaerocarpa* (L.) Boiss), on soil moisture patterns. We fitted a process-based model of soil moisture dynamics under an intermediate and high emissions scenario (i.e. RCP4.5 ad RCP8.5; van Vuuren et al., 2011), to estimate the concurrent impact of shrub encroachment and climate change. We intend to answer: i) How does shrub encroachment affect soil water availability in Mediterranean wood-pastures? ii) How does it impact the onset and duration of seasonal drought under current and future climate? iii) How is the inter-annual variability of soil moisture affected by the presence of shrubs? We hypothesised that shrub encroachment will affect the timing and duration of drought stress. However, the magnitude of this effect might be dependent on the type of shrub present. We expect that these effects will be magnified under future climatic scenarios. Understanding the concurrent effect of changes in ecosystem structure and climate change on the trends of soil moisture is of major importance to assess the vulnerability of degradation of Mediterranean wood-pastures.

2. Material and methods

2.1. Study site

The study sites are located in the northern part of the Extremadura region (western Iberian Peninsula, 40°2'34.98"N, 5°54'50.98"W) (Fig. 1). The vegetation of the area is a savanna-like open woodland, called dehesa in Spain. The dehesa system is a prominent example of Mediterranean wood-pasture in Europe, where a mosaic of scattered trees (mainly *Quercus ilex*), shrubs and open pastures of mostly annual species shape its landscape (Moreno and Pulido, 2009). All study sites are located in flat or gently sloping areas with oligotrophic and acidic soils. The climate of the area is Mediterranean with hot, dry summers and mild, rainy winters. Mean annual precipitation and temperature during the study period was 588 mm and 17.1 °C (2009–2012; Plasencia meteorological station). However, in 2009, the annual rainfall was ~45% lower than the historical mean (697 mm, 1961–1998) and in 2012 winter precipitation was ~90% lower as compared to the historical trend (267 mm winter precipitation 1961–1998) (Fig. S1).

2.2. Study design and soil water content measurements

We selected a total of six sites, distinguishing between sites where *Cistus ladanifer* (*Cistus*, hereafter) was the shrub species present (three), and sites where *Retama sphaerocarpa* (*Retama*, hereafter) was the shrub species present (three) (Fig. 1). All sites had two adjacent plots, similar tree cover, soil type and slope (Table S1), but differing in the presence of shrubs (i.e. with and without shrubs, encroached and control plot respectively). Four different micro-habitats were defined in each site: beneath the tree canopy and away from the tree canopy (>20 m from nearest tree) in control and encroached plots (tree, open,

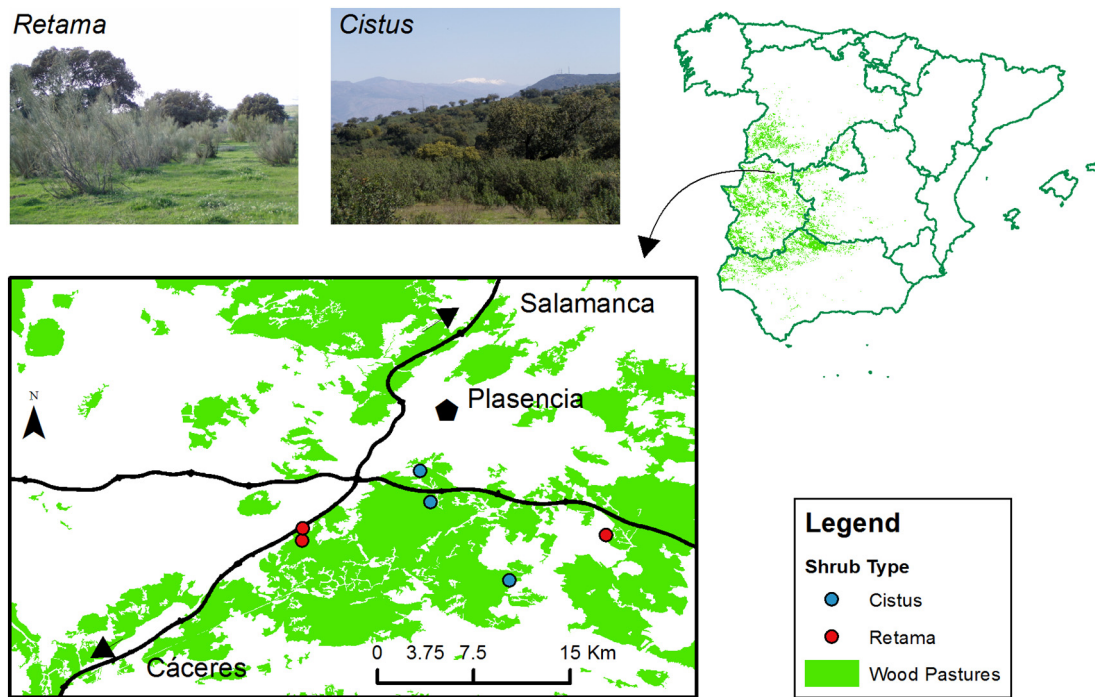


Fig. 1. Map depicting the extent of Mediterranean wood-pastures (i.e. Dehesa) in Spain. Inset indicates the location of studied sites encroached either with *Cistus* or with *Retama*. Photographs show an overview of encroached plots of *Retama* and *Cistus* sites. Note the contrasting vegetation structure between site types.

shrub and tree + shrub, respectively). Both shrubs are extensively distributed in the studied region where they mainly form monospecific stands, but they represent two contrasted ecological functions. *Cistus* is a shallow-rooted shrub (≈ 1 m, Rolo and Moreno, 2012) that forms high cover population and diminish tree and pasture production (Rivest et al., 2011a). *Retama* is a leafless N-fixing, deep-rooted shrub (> 10 m, Haase et al., 1996) individuals of which are sparsely distributed and positively affects pasture production (Rivest et al., 2011a) mainly due to the amelioration of abiotic conditions (Pugnaire et al., 2011). Overall, Mediterranean wood-pastures encroached by *Cistus* tend to have less foraging capacity than that encroached by *Retama* (López-Díaz et al., 2015).

We measured soil water content for four consecutive years (2009–2012) using Diviner 2000 (DV) (Sentek Sensor Tech., Stepney, Australia) in two sites, and time-domain reflectometry method (TDR) in four sites (Table S1). Four access DV tubes per micro-habitat were placed down to 120 cm in the *Cistus* site and 160 cm depth in the *Retama* site in spring 2009. We recorded soil water content every 10 cm from April 2009 to December 2012. In the TDR sites, three 20 cm long TDR probes were placed at 0, 30, 50 and 100 in *Cistus* and *Retama* sites in spring 2008 following Cubera and Moreno (2007). TDR measurements were taken from January 2009 to February 2011 using a Tektronix 1502-C cable tester (Tektronix communications, Plano, Texas, USA). TDR soil moisture was determined using the relationship established by Topp et al. (1980). We assume that both TDR and DV measurements are equivalent as they were highly correlated ($r = 0.88$, $P < 0.001$) and we did not observe significant differences between them ($t = 1.3$, $df = 41.7$, $P = 0.204$). Additionally, to improve the comparison of soil moisture values among sites, we expressed it as relative extractable water (REW). Relative extractable water ranges between 0 and 1 and describes the ratio between actual available soil water and maximum extractable water, the difference between field capacity and permanent wilting point (Granier et al., 1999). Soil water content at field capacity and permanent wilting point was calculated following the pedotransfer functions of Saxton et al. (1986) using the soil texture functions of the R package “medfate” (Cáceres et al., 2015). Soil samples were collected from two different depths representative of the topsoil (~ 10 cm) and

subsoil (~ 40 cm) and for each micro-habitat in a *Retama*, and a *Cistus* site and texture classes were measured by the pipette method.

2.3. Climatic variables and drought stress indices

Daily climatic variables (rainfall and maximum and minimum temperature) for the period from 2009 to 2012 were provided by the Spanish Meteorological Agency (AEMET) for the meteorological station located in Plasencia (Fig. S1). This station was located no further than 15 km away from the study sites and there were no major geographical obstacles between them. We used the Hargreaves-Samani equation for calculating potential evapotranspiration (mm) using the R package “fireDanger”.

We defined two indices of drought stress following Bréda et al. (2006). Namely: start of drought stress as the day of the year (DOY) below a REW threshold of 0.4; and drought stress duration as the length of the period between the start and cessation of drought stress. We used a threshold of 0.4 because below this value the stomatal regulation of trees is induced and there is a reduction of stand transpiration (Bréda et al., 2006). Similarly, the canopy conductance of many Mediterranean woody species is reduced significantly once soil water potential falls below -0.5 MPa (Limousin et al., 2009). Values of REW below 0.4 have been associated with predawn leaf water potentials below -1 MPa (Grossiord et al., 2017), supporting the use of this threshold as a proxy for water stress.

2.4. Soil water balance modelling and climatic scenarios

To characterise drought stress during the observed period (2009–2012) and future climatic scenarios (2020–2100), we estimated daily relative extractable water using the water balance model “medfate” (Cáceres et al., 2015). The medfate model is based upon BILJOU and SIERRA water balance models (Granier et al., 1999; Ruffault et al., 2013) and estimates daily updates of soil water content as a function of stand structure properties, daily climatic variables and soil properties. Soil water content at a given time and depth is calculated as the difference between water input (precipitation) and outputs

(canopy interception, tree transpiration, bare soil evaporation, surface runoff and deep drainage) (Cáceres et al., 2015). Soil was included as two layers (topsoil and subsoil) with a total depth of 120 cm and a rock layer up to 200 cm. We included site-specific soil texture values measured for each layer. The proportion of fine roots of each plant and soil layer was obtained from Rolo and Moreno (2012). Stand structure properties are included in “medfate” as the cohort level for each species as the average height and cumulative leaf area index. To estimate leaf area index values of trees and shrub micro-habitats, we acquired hemispherical photographs with a 180° field of view lens mounted in Nikon Coolpix 995 camera (Nikon Corporation, Tokyo, Japan) in 2010. For the herbaceous layer, we used data from a similar wood-pasture than the study sites (Perez-Priego et al., 2015). Species specific parameters of water potential corresponding to 50% relative conductance for trees and shrubs, and generic for the herbaceous layer were obtained from the literature (Table S2). To improve model performance and estimate unmeasured variables (e.g. rock fragment content), we used a generic optimisation algorithm (DEoptim, Mullen et al., 2009). We evaluate the predictive accuracy of water balance models by comparing simulated and observed relative water content values in encroached and control plots (Fig. S2).

For future climatic projections, we considered two climatic scenarios developed for the Fifth Report of the IPCC (2014): the Representative Concentration Pathway 4.5 and 8.5 (RCP4.5 and RCP8.5 respectively). The RCP4.5 and RCP8.5 set an increase of the radiative forcing of 4.5 and 8.5 watts per square meter by 2100 relative to pre-industrial values, respectively. The RCP8.5 is the “business as usual” pathway where greenhouse gas emissions continue to rise throughout the 21st century (van Vuuren et al., 2011). The RCP4.5 represents an intermediate mitigation scenario, where greenhouse gas emissions peak by mid-century and then start to decline (van Vuuren et al., 2011). AEMET provided multimodel ensemble means of future climatic projection data statistically downscaled for the meteorological station of Plasencia (Rodríguez and Gutiérrez, 2018). The projected climate predicts a reduction of 17.0% (from 542 to 449 mm) and 7.4% (from 569 to 527 mm) of annual precipitation and an increase of 31.9% (from 16.3 to 21.5 °C) and 12.0% (from 16.5 to 18.4 °C) of mean temperature by 2100 under RCP8.5 and 4.5, respectively (Fig. S2). For each simulated scenario, we computed drought onset and duration, the proportion of water transpired from deep soil layers and the inter-annual variability, expressed as the coefficient of variation (Sloat et al., 2018).

2.5. Data analysis

To assess the temporal dynamics of relative extractable water among micro-habitats for the period from 2009 to 2012, we fit a linear mixed model (LMM), with month, year, micro-habitat and the interaction between year and micro-habitat as fixed effects and two random effects. The random part of the model included a random intercept for each profile and a random slope for month. We fit a random intercept and slope model, to account for repeated measures of relative extractable water for each profile over time (Bates, 2010). The effect of month was included as a quadratic trend to allow for the non-linear pattern of soil moisture during the year. We manually set specific contrast to test for differences at the plot and micro-habitat level. We fit separate models for *Cistus* and *Retama* sites.

To evaluate if drought onset, duration, and the proportion of water transpired from deep soil layers computed using the soil water balance model varied between control and encroached plots for the observed period (2009–2012), we fit linear mixed models including the interaction between micro-habitat and year as fixed effects. For future climatic scenarios, we assessed the statistical significance of temporal trends of drought indices using the Theil-Sen approach. All statistical analyses were performed using R version 3.4.2 (R Core Team, 2017).

3. Results

3.1. Spatio-temporal dynamics of relative water content

Woody micro-habitats showed, in general, lower soil moisture values than the open micro-habitat (Figs. 2 and S3). Mean relative extractable water (REW) was significantly lower in encroached than in control plots of *Cistus* sites (0.42 ± 0.01 and 0.47 ± 0.01 , REW \pm SE in encroached and control plots, respectively; $P = 0.020$) during the observed period (2009–2012). The significant reduction of REW in encroached plots of *Cistus* sites was mostly driven by the tree + shrub micro-habitat that consistently showed lower REW values than the open micro-habitat (Fig. 2B). The shrub micro-habitat significantly reduced REW in 2009 (0.27 ± 0.01 and 0.34 ± 0.01 , REW \pm SE in shrub and open micro-habitat) and 2011 (0.55 ± 0.01 and 0.63 ± 0.01 , REW \pm SE in shrub and open micro-habitat) ($P < 0.001$, respectively).

In *Retama* sites, there were no differences in REW between plots during the observed period (0.44 ± 0.01 and 0.43 ± 0.01 , REW \pm SE in encroached and control plots, respectively; $P = 0.539$). When considering each micro-habitat separately, only the tree + shrub micro-habitat significantly reduced REW as compared to open spaces in 2012 (0.16 ± 0.01 and 0.25 ± 0.01 , REW \pm SE in tree + shrub and open micro-habitat; $P < 0.001$; Fig. 2D).

The tree micro-habitat showed a neutral to negative effect on REW as compared to the open micro-habitat (Fig. 2B and D). In *Cistus* sites, the tree micro-habitat significantly reduced REW in 2009 and 2012 ($P < 0.001$, respectively) and in 2011 and 2012 ($P = 0.030$ and $P = 0.006$, respectively) in *Retama* sites.

3.2. Simulated drought stress

Simulated REW for the study period fitted observed data well (Table S3). Predicted and measured REW were significantly correlated for all plots ($r = 0.75 \pm 0.03$ and $P < 0.001$ for all plots). In general, predictions mimicked measured REW, following both inter-annual and plot level patterns (Fig. S3). However, there were certain mismatches between predicted and measured values at the plot level. Mismatches were related to lower predicted REW in encroached than control plots whereas observed values showed the opposite trend (Site 1 in 2012 and Site 3 in 2010, Fig. S3). These inconsistencies indicate that there was certain inter-annual variability at the plot level that was not well accounted for by the model. Nevertheless, the accuracy of the simulation was reasonably good as predicted REW closely matched measured REW (RMSE = 0.17 ± 0.01).

In line with observed measurements, model simulations showed that shrubs consistently worsened drought indices from 2009 to 2012 as compared to control plots (no significant interaction between micro-habitat and year; Table 1). Only for deep water transpiration in *Retama* sites, the interaction between micro-habitat and year was significant ($P = 0.015$), yet this interaction was driven by a sharp increase in deep water transpiration in the encroached plot in 2009. In general, encroached plots showed higher transpiration from deep soil layers (~30% increase in encroached plots of both *Cistus* and *Retama* sites) and more extended periods of drought (29 and 48 days longer in encroached in *Cistus* and *Retama* sites, respectively). The effect on the onset of drought was less intense, yet both types of shrubs tend to show an earlier onset of drought in encroached plots as compared to control plots (16 and 30 days earlier in encroached than control plots in *Cistus* and *Retama* sites, respectively).

3.3. Soil water balance simulations at varying climatic scenarios

Projections showed a significant increase in drought duration and a decrease in its onset by the end of the century in control and encroached plots of *Cistus* and *Retama* sites (Figs. 3 and 4). This pattern was particularly strong under the worst climatic scenario (i.e. RCP8.5), showing

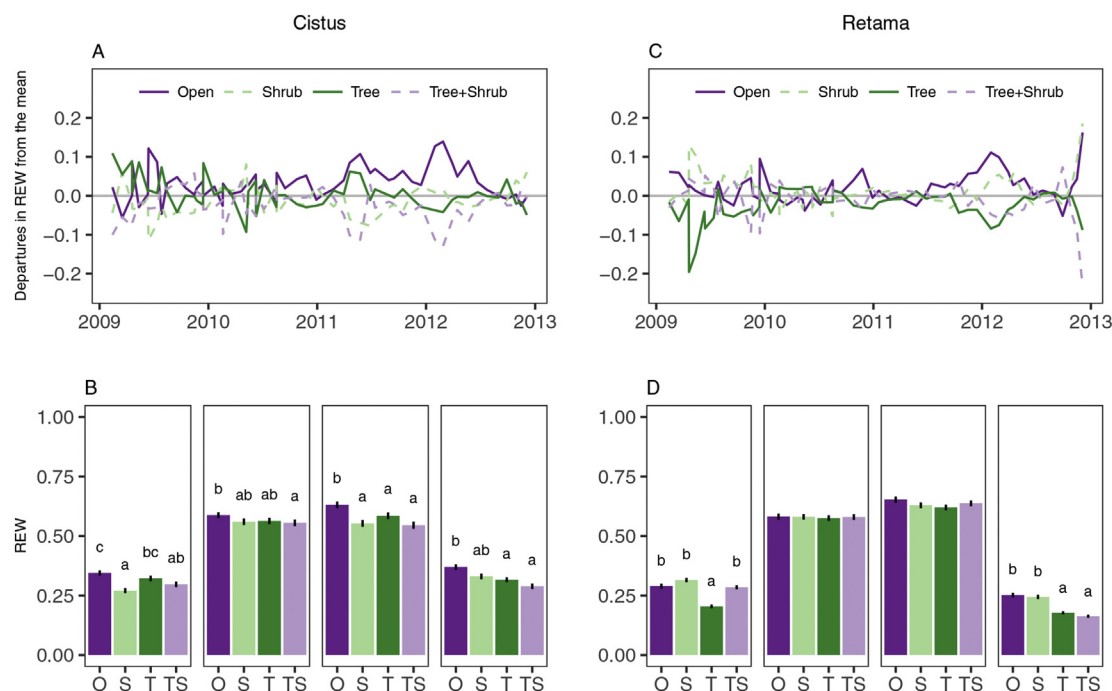


Fig. 2. Temporal dynamics of REW for each micro-habitat in *Cistus* and *Retama* sites during the period of 2009–2012. Upper panels show the deviation in REW from the mean for each sampling date. Lower panels depict mean REW (\pm S.E.) of each micro-habitat (O: open; S: shrub; T: tree and TS: tree + shrub) for each year separately. Letters within each panel indicate significant differences among micro-habitats at $P < 0.05$.

stronger temporal trends of drought duration and onset than under the RCP4.5 scenario. The temporal patterns of deep transpiration were significantly different between control and encroached plots both in *Cistus* and *Retama* sites (Figs. 3A and B and 4A and B). Whereas in the control plot, we observed a significant increase in the usage of deep water with time, in the encroached plot we found the opposite pattern, with no effect in the RCP4.5 scenario or a significant reduction in the RCP8.5 scenarios.

Simulated trends of drought indices showed a higher variability in encroached than control plots (Table 2). In *Retama* sites, most drought indices showed significantly higher values of inter-annual variability, except drought onset in the RCP4.5. In *Cistus* sites, there were significantly higher values of the inter-annual variability of drought onset and deep water transpiration in the encroached than in the control plot.

4. Discussion

Climate changes in Mediterranean regions are expected to increase the exposure to drought of livestock grazing systems (Daliakopoulos et al., 2017; Falloon and Betts, 2010). Our results accord with this general trend and show that by the end of the century there will be an increase in the duration and a reduction in the onset of drought and a shift in the usage of deep water, particularly under the worst climatic scenario (RCP8.5). Moreover, our results suggest that processes of shrub encroachment can exacerbate these effects by affecting both the

timing of droughts (onset and duration) and the profile of soil water uptake, yet this effect is partly controlled by the functional type of shrub present.

4.1. Drought, climate change and shrub encroachment

Our result showed that the presence of shrubs worsened all drought indices, indicating that processes of shrub encroachment may lead to prolonged and more intense droughts in the following decades. In addition, shrubs will shift the profile of water usage with a higher dependency on surface moisture under the worst climatic scenario. Indeed, it has been suggested that, by the end of the century, vegetation would be more dependent on surface moisture, affecting to a large extent the provision of ecosystem services (Schlaepfer et al., 2017).

In systems encroached by shrubs, a pervasive reduction of soil moisture in the long-term may trigger the transition towards a degraded state (D'Odorico et al., 2012). Increasing droughts has been related to higher incidence of tree mortality events, more frequent wildfires and shifts in plant functional types (Williams et al., 2010). The significant increase in inter-annual variability in encroached plots further supported the long-term effects of shrub encroachment on ecohydrological processes. High inter-annual variability exerts a long-term control on water resources, constraining vegetation productivity of grazing systems globally (Sloat et al., 2018). In scattered tree systems, it has been proposed that the high dynamism of herbaceous vegetation can buffer

Table 1

Mean values (\pm SE) of drought indices computed with the soil water balance model from 2009 to 2012 in encroached and control plots of *Cistus* and *Retama* sites.

	<i>Cistus</i>			<i>Retama</i>		
	Control	Encroached	<i>P</i> -value	Control	Encroached	<i>P</i> -value
Deep Transpiration, %	37.1 \pm 2.9	47.3 \pm 1.7	0.038	36.6 \pm 2.4	47.8 \pm 2.4	0.001
Duration, days	118.8 \pm 8.7	148.0 \pm 10.4	0.004	130.2 \pm 9.7	177.9 \pm 18.5	0.007
Onset, DOY	186.8 \pm 4.7	170.5 \pm 9.7	0.060	179.5 \pm 6.1	150.0 \pm 18.6	0.056

Italics depict marginally significant differences at $0.05 < P\text{-value} < 0.10$.

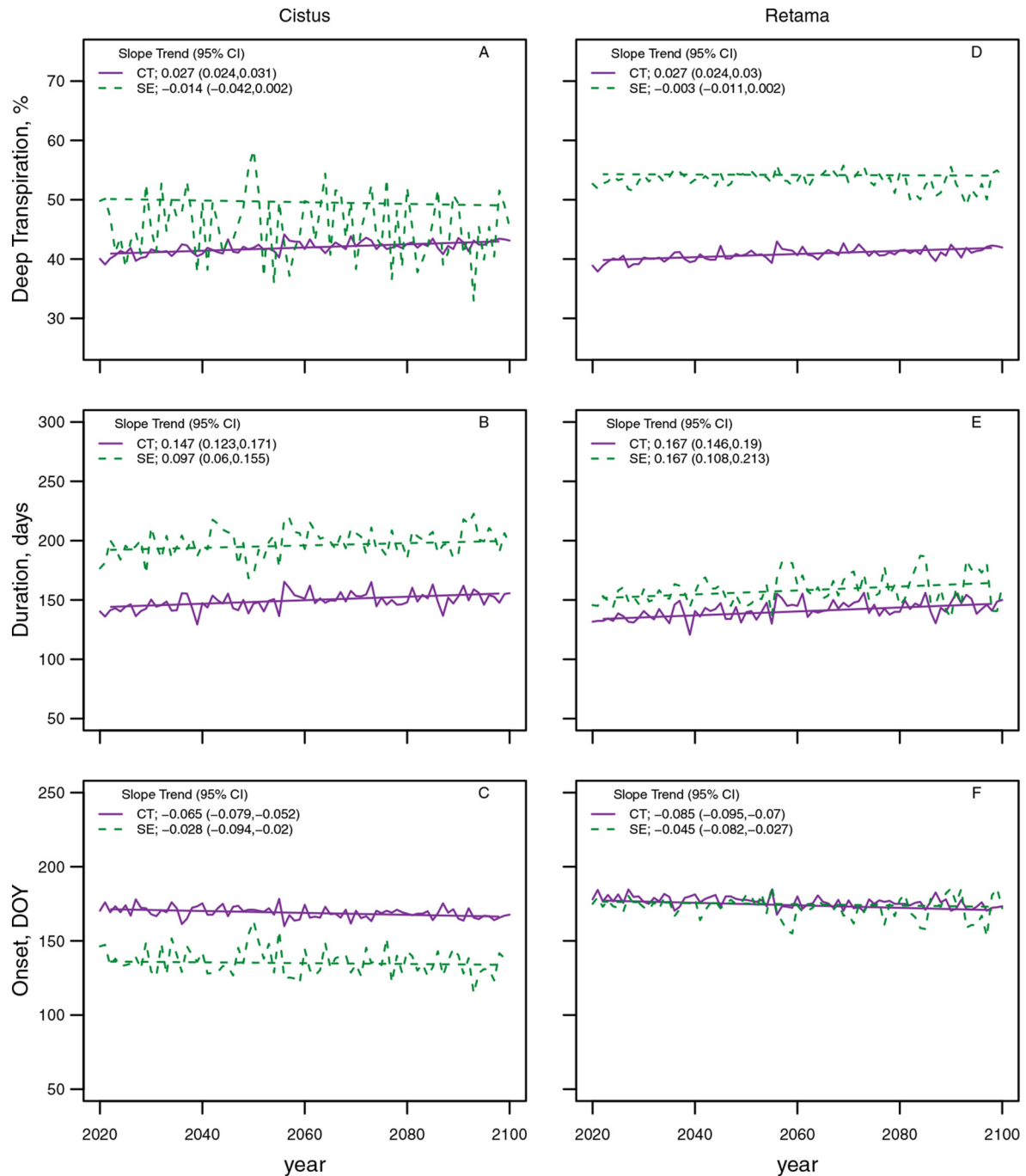


Fig. 3. Simulated drought indices for the period from 2020 to 2100 under the RCP4.5 scenario in control (C) and encroached plots (S). Figures insets depict slope values \pm 95% CI.

the adverse effects of inter-annual variability on the system functioning (Scanlon et al., 2005). For instance, inter-annual variation in herbaceous biomass may lead to higher stability in the recharge of deeper soil layers (Scanlon et al., 2005). By contrast, the longer life-span of woody shrubs may disrupt this equilibrium, and shift the dynamic of the system towards alternative stable states, which ultimately may lead to the degradation of the system if the aridity increases (Mayor et al., 2013).

4.2. Influence of shrub functional type on soil water dynamics

Our results agree with the notion that shrubs with varying functional characteristics affect ecohydrological processes differently. *Cistus*

showed a predominantly negative effect on soil moisture, particularly when in combination with trees. Both a direct usage and an increased interception are two ways by which *Cistus* shrubs can reduce soil moisture values. The adverse effect of *Cistus* in years of high water availability may accord with this notion. An individual of *Cistus* can intercept up to 21% of the precipitation that reaches the crown (Simões et al., 2009). This value is similar to that reported for *Q. ilex* (David et al., 2006). Given the high density of *Cistus* populations (~70%), the losses of rainfall in a ground area basis can be a considerable amount regarding the overall water balance, particularly in combination with trees.

Contrary to *Cistus*, *Retama* did not affect soil moisture during the studied period. The deep root system of *Retama* suggests high usage of deep

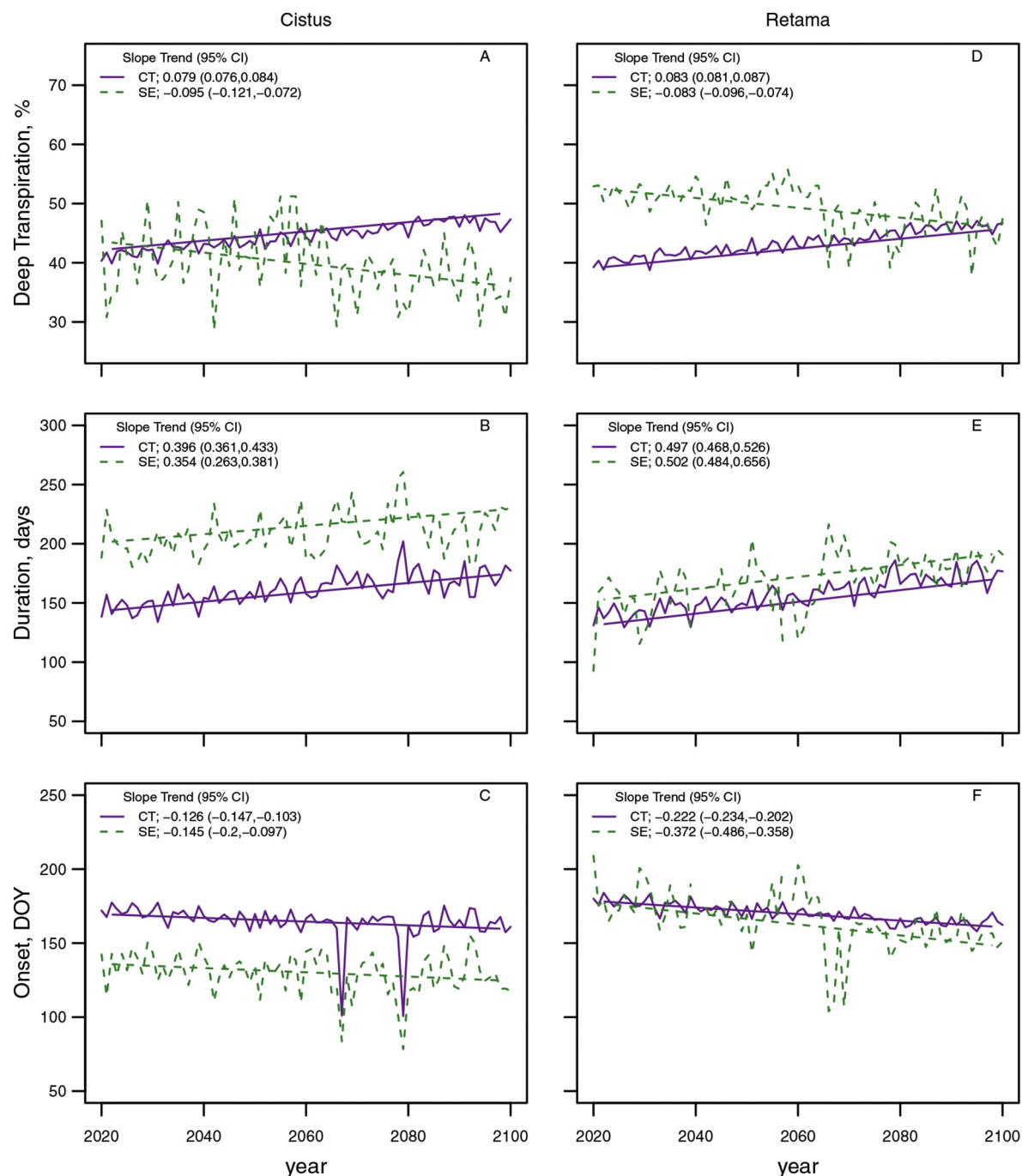


Fig. 4. Simulated drought indices for the period from 2020 to 2100 under the RCP8.5 scenario in control (C) and encroached plots (S). Figures insets depict slope values \pm 95% CI.

Table 2

Coefficient of variation and bootstrapped 95% CI as a proxy of inter-annual variability of drought indices in control (CT) and encroached (SE) plots under two climatic scenarios. Bold numbers depict significant differences (i.e. non-overlapping 95% CI) between plots. Note that coefficient of variation values are express as percent.

			Deep Transpiration	Duration	Onset
Cistus	RCP4.5	CT	2.5 (2.1, 2.8)	4.8 (4, 5.5)	2.3 (1.9, 2.6)
		SE	11.7 (10.1, 13.1)	5.8 (4.9, 6.6)	6.7 (5.6, 7.7)
	RCP8.5	CT	4.7 (4.1, 5.2)	7.9 (6.6, 9.1)	7 (3.1, 10.2)
		SE	14.1 (12, 16)	8.2 (6.9, 9.5)	10.7 (8.3, 12.9)
Retama	RCP4.5	CT	2.4 (2.1, 2.8)	5.1 (4.4, 5.8)	2.1 (1.8, 2.4)
		SE	2.7 (2.2, 3.1)	7.9 (6.7, 8.8)	4.2 (3.5, 4.8)
	RCP8.5	CT	5 (4.3, 5.5)	8.7 (7.5, 9.8)	3.6 (3.1, 4)
		SE	7.8 (6.2, 9.1)	15.1 (12.1, 17.9)	12.1 (9.4, 14.5)

soil water and, therefore, low competition in the uppermost soil layers. Indeed, it has been shown that *Retama* roots can reach up to 16 m depth (Haase et al., 1996). Additionally, this shrub has been shown to redistribute water from deep to the uppermost soil layers (i.e. hydraulic lift, Prieto et al., 2010). Thus, the lack of effect may result from the combined influence of low usage in the uppermost soil layers and shading which can reduce the losses due to evaporative demand (Villegas et al., 2010). This evidence agrees with the commonly observed facilitative effect of this shrub species in its understory (Rivest et al., 2011a). Nevertheless, a decline on water potential of trees growing with *Retama* has been observed by the end of the dry season (Rolo and Moreno, 2011), suggesting that the adverse effect of this shrub on nearby vegetation may become evident only when the availability of water is scarce.

4.3. Limitations

One limitation of our study is that we have assumed a static vegetation structure during the simulation procedure. This may have resulted in the overestimation of the effects of climate change on drought, as processes of adaptation of vegetation structure to climate were not considered. The modelling effort did not consider either the likely fertilization effect on plant water relations due to increases in atmospheric CO₂, particularly under the RCP8.5 scenario. Rising atmospheric CO₂ concentrations may increase river runoff because of a reduction in plant transpiration (Gedney et al., 2006). Although the hydrological impact of rising CO₂ is still a matter of debate, recent studies indicate that this effect may be comparatively small if land use changes are taken into account (Piao et al., 2007). Nevertheless, our results agree with modelling efforts that iteratively adapt the indirect effect of vegetation on soil water availability throughout the simulation, and predict an increased effect of woody vegetation cover and growth magnifying the impact of climate change on soil moisture (Tietjen et al., 2017). Additionally, predicted socioeconomic changes in the study region suggest that the presence of shrub will increase because of the progressively abandonment of marginal lands, indicating that it would be more likely that areas devoid of shrubs would become encroached than vice versa.

4.4. Conclusions

Overall, we found that, despite the functional differences between shrub species, both types of shrubs will reduce soil water availability, increasing the duration of seasonal droughts. These effects will be particularly relevant under the RCP8.5 scenario. However, even for the milder RCP4.5 scenario, the increase in inter-annual variability in the encroached plots indicates that cycles of extreme events may be exacerbated (Anderegg et al., 2013), affecting the productivity of the system and resulting in a likely reduction of the capacity of livestock grazing (Sloat et al., 2018). Processes of shrub encroachment together with climatic changes pose the question of how off-site effects, such as downstream impacts in river catchments, will be affected. The likely expansion of shrubs due to the abandonment of unprofitable rainfed farming under future scenarios may magnify these off-site effects (Nainggolan et al., 2012). In a context where the pressure on available water resources may increase, processes of shrub encroachment may constitute an additional hindrance to food security and economic prosperity in arid and semi-arid regions of the world. Policies and management strategies that aim to revert this trend have been recently encouraged in order to guarantee access to water resources, contributing, therefore, to Goal 6 of the Sustainable Development Goals (United Nations, 2015). In this line, it has been argued that shrub clearing is an opportunity to re-organise landscape elements in marginal areas while reducing negative impacts on water availability (Lasanta et al., 2015). However, the viability of active shrub clearing has been questioned given the high economic and labour costs and the low success rate in the long-term (Archer, 2010). Understanding to what extent various activities to control shrub encroachment, from clearing to integrated systems (Noble and Walker, 2006), will affect soil water availability is a key step to promote the resilience of Mediterranean wood-pastures in a scenario of climate change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.01.029>.

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